

Cascading Failures: Earthquake Threats to Transportation and Utilities
Abbreviated Report

December 2014

ASSOCIATION OF BAY AREA GOVERNMENTS

Item 8, Attachment 1

Cascading Failures: Earthquake Threats to Transportation and Utilities

December 2014

Want to dive into a full report? Download the detailed report to understand the impacts of infrastructure failure on the Bay Area.

Report: resilience.abag.ca.gov/projects/transportation_utilities_2014



Association of Bay Area Governments

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EXECUTIVE SUMMARY

The operability of airports following a major earthquake is dependent upon minimal facility damage and functioning infrastructure systems. The immediate operation of airports provide valuable air functions during disaster response, and are a necessity for quick recovery of societal and economic functions. The San Francisco Bay Area is fortunate to have 24 public airports (Oakland International and North Field are considered separate), one federal airport, and one military airport which together provide a redundant network of runways across the nine county region. This network however, will be stressed by a major hazard event.

In the Bay Area a number of earthquake faults can produce strong shaking and significant damage in all nine counties. A single earthquake event is unlikely to cause damage at every Bay Area airport, but damage to key infrastructure systems could result in outages at many or all airports. A geographically dense fuel system and a single electric system service the whole Bay Area and neighboring counties outside the region. A complete outage of either would impact all airports. The water and transportation networks, while more redundant, could also experience large outages that impact many airports simultaneously. To properly mitigate seismic risk, airports and other stakeholders must improve infrastructure reliability alongside improvements to airport facilities.

This report maps airports, roadways, passenger rail, fuel, electric, and water systems, and highlights their interaction with seismic hazards. Publicly available information is used to describe each system to gain a high-level understanding of how the system operates, and the potential consequence should the system be damaged. The report does not state specific restoration timelines nor damage estimates, but does reference restoration timelines experienced in past comparable events. Instead, the report focuses on the seismic exposure of many systems and their significant consequence for airports and other stakeholders. The key findings warrant keen attention from regional and state actors.

Key Findings

Airports

- Airports are well distributed around the region.
- In San Andreas and Hayward scenario events the three international airports will simultaneously experience strong to violent shaking. 19 of 26 Bay Area airports are within five miles of an active Alquist-Priolo mapped fault, and 23 of 26 are within ten miles.
- Of the 24 airports that completed the Caltrans Division of Aeronautics Emergency Plan Survey, 21 have an Airport Emergency Plan, 16 of which have sections that cover earthquakes.

Ground Transportation

- San Francisco International Airport (SFO) and Oakland International Airport (OAK) are near parallel highway networks: I-280 & US 101 at SFO, and I-880 & I-580 at OAK. These parallel roadways will be subject to different hazards in San Andreas and Hayward events, with the inland routes (I-280 & I-580) experiencing violent and very strong ground motions, and the bay side routes (I-880 & US 101) experiencing liquefaction as well as very strong ground motions.
- Large-scale seismic retrofit programs have resulted in much more resilient rail and highway networks. Still, a single failure along non redundant corridors can severely disrupt travel.

Fuel

- Fuel refineries are likely to have correlated performance, if one is damaged it's likely others are damaged too. A conservative restoration estimate of damaged refineries is months.
- Damage to the fuel transmission system would severely impact counties beyond Solano and Contra Costa where most refineries are located. Transporting the normal fuel demand by truck after a disaster simply is not feasible.
- Damage to pipes that cross the Bay, or an inability to pump fuel east would cause fuel supply interruptions across Northern California and Nevada.

Electric

- Damage to the region's electric generation facilities along the Carquinez Strait, or interruption in the natural gas system could result in long power supply interruptions.
- In the immediate aftermath, most critical facilities (including airports) plan to use fuel-powered generators to restore electric services. The interruption of fuel could limit this backup capacity and delay immediate restoration of service.

Water

- Most of the 11 Bay Area water districts studied have multiple water sources or have invested in robust, redundant, and repairable systems that contribute to system resilience. When reservoirs and groundwater reserves are above half full there is significant regional water storage available if regional systems require repair. Distribution pipeline failures will govern service for many.
- Restoration of water distribution systems in areas of liquefaction can require weeks to months. The region's three international airports, and a number of general aviation airports located on the bay margins, are in liquefaction susceptibility zones.
- Agencies dependent on Delta water would be significantly impacted if levees failed, causing flooding and salt water intrusion.

Functional infrastructure systems are necessary for achieving community resilience. The consequence of infrastructure damage cascades well beyond the costs to repair the immediate damage. The failure of one system limits the functionality of other key regional assets, like airports, and will cause interruption for both households and businesses. While it is unrealistic to expect systems to be earthquake proof, knowing what to expect provides the users of infrastructure systems the information they need to take measured preparedness actions. Currently the vulnerability of many infrastructure systems is not well known or not well communicated to the public. With a lack of information, airports have no baseline for predicting the benefits of possible preparedness or mitigation strategies. Going forward, the region must understand and communicate the vulnerability of infrastructure systems to inform stakeholders on what to expect so that they can make informed decisions to limit their impacts should systems fail.

This study is a first step in understanding the risks to transportation, fuel, electric, and water systems. The report should be used to inform actions in the present, and also as a call for greater study of the region's infrastructure systems, and their impact on Bay Area stakeholders.

INTRODUCTION

"We rarely see in full the cities that we live in. Focused on our daily lives, urban dwellers are often only dimly aware of the numerous, enmeshed layers of critical infrastructure that quietly hum in the background to make modern life possible." - Macro City, 2014

It is when infrastructure fails that we become keenly aware of our reliance, and the cascading impact a single failure has across multiple systems, sectors, and processes. Degrading infrastructure systems and future large earthquakes with epicenters near critical regional infrastructure could result in system outages that last weeks for the most reliable systems, and multiple months for others.

This report maps airports, passenger rail, roadways, fuel, electric, and water systems, and highlights their interaction with seismic hazards. We used publicly available information to describe how each system operates, and the consequence of system damage. The key findings warrant a transparent public discussion of the reliability the region desires for its vital infrastructure systems.

BAY AREA EARTHQUAKE HAZARDS

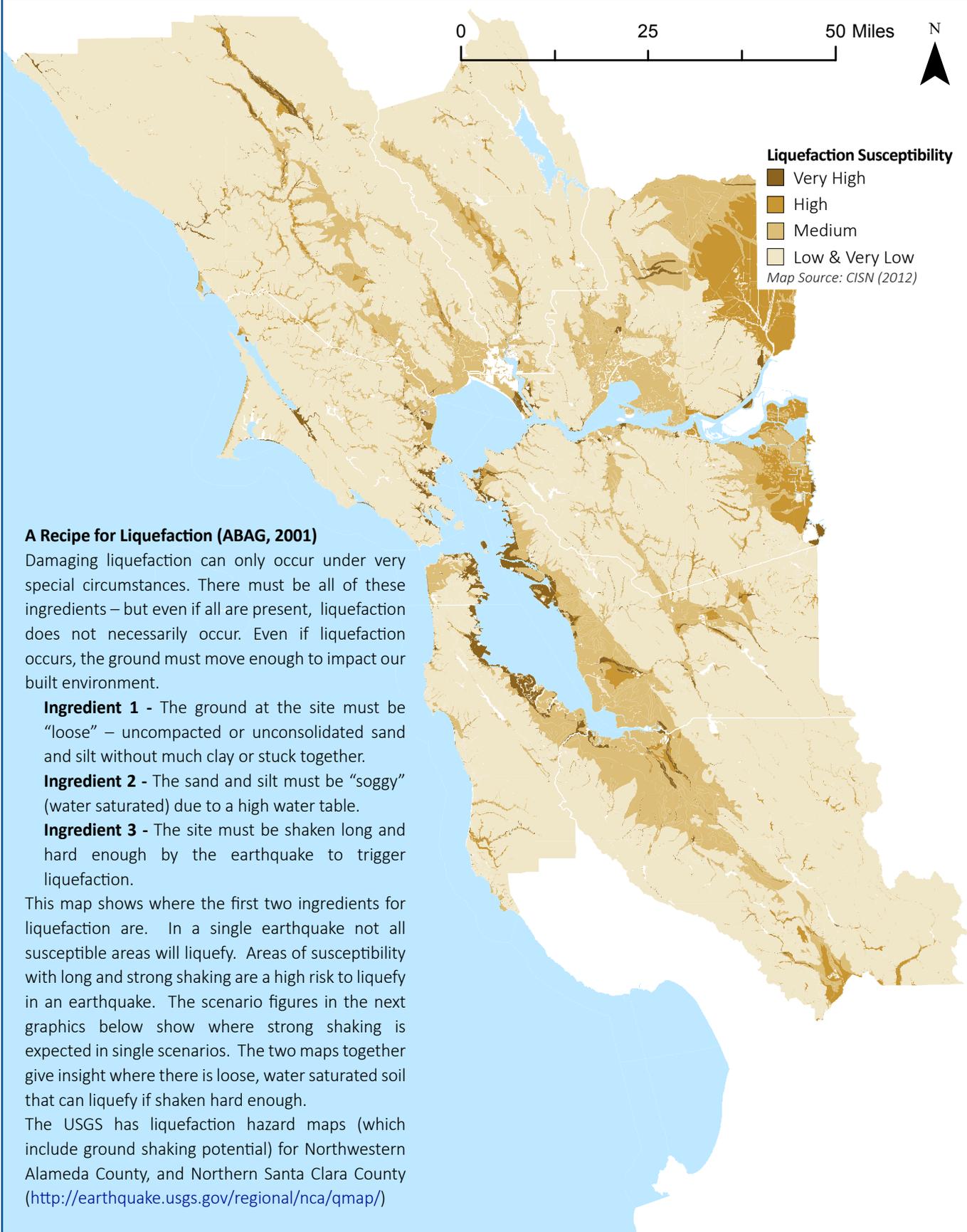
We studied three earthquake faults that could cause damage to infrastructure systems and impact the entire Bay Area. San Andreas, Hayward, and Concord scenarios produce strong shaking across large areas that are dense with regional infrastructure systems. Other faults can have significant local impacts, but are not explored in this report.

It's not just ground shaking and fault rupture that can damage buildings and infrastructure; liquefaction is often a much more damaging earthquake effect for linear infrastructure systems. Explore liquefaction susceptibility and scenario earthquake ground shaking maps on the following pages.



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Lateral spreading (a form of liquefaction) at the Coronel Port container yard following the M8.8 2010 Maule, Chile earthquake.



A Recipe for Liquefaction (ABAG, 2001)

Damaging liquefaction can only occur under very special circumstances. There must be all of these ingredients – but even if all are present, liquefaction does not necessarily occur. Even if liquefaction occurs, the ground must move enough to impact our built environment.

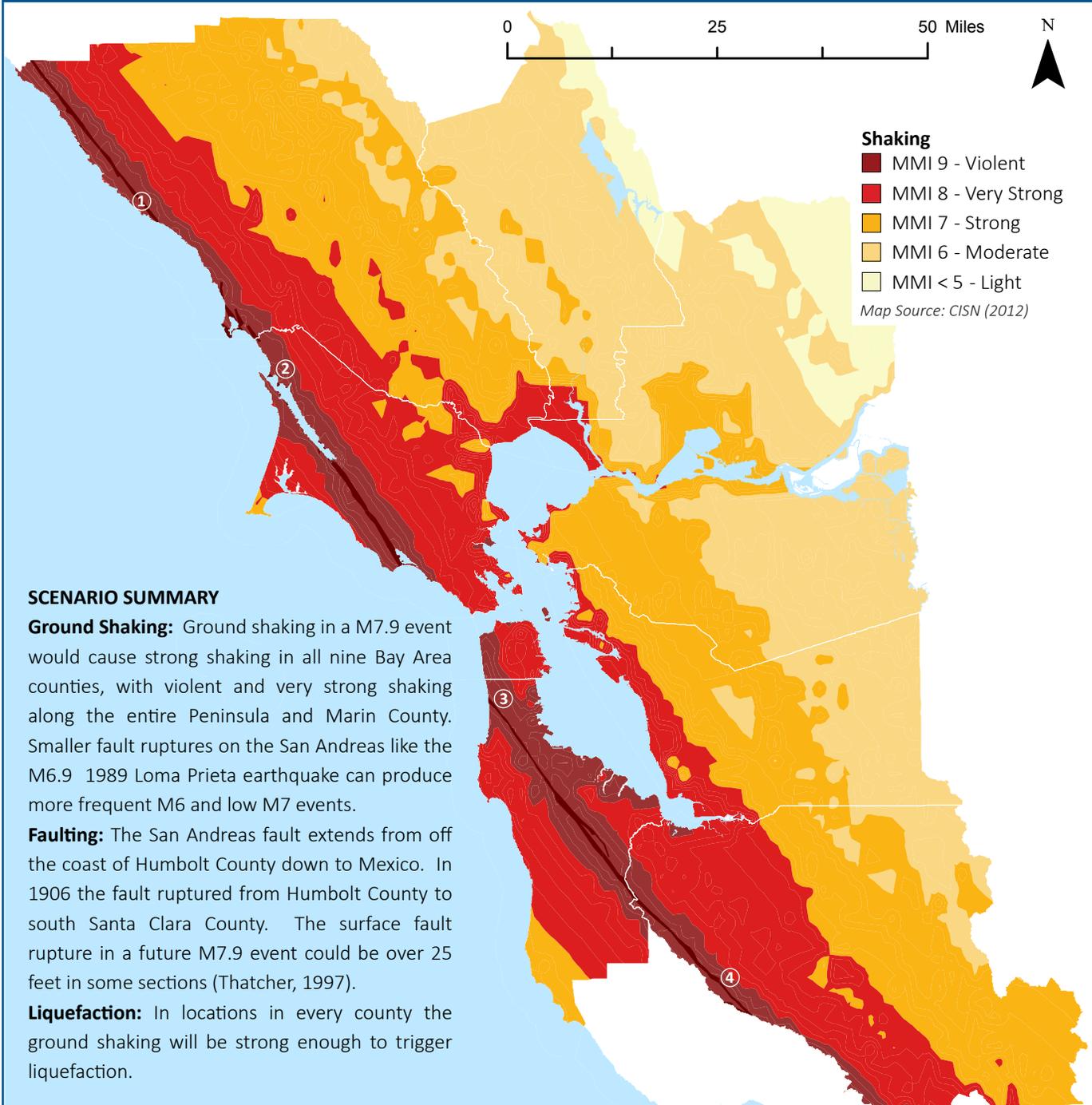
Ingredient 1 - The ground at the site must be “loose” – uncompacted or unconsolidated sand and silt without much clay or stuck together.

Ingredient 2 - The sand and silt must be “soggy” (water saturated) due to a high water table.

Ingredient 3 - The site must be shaken long and hard enough by the earthquake to trigger liquefaction.

This map shows where the first two ingredients for liquefaction are. In a single earthquake not all susceptible areas will liquefy. Areas of susceptibility with long and strong shaking are a high risk to liquefy in an earthquake. The scenario figures in the next graphics below show where strong shaking is expected in single scenarios. The two maps together give insight where there is loose, water saturated soil that can liquefy if shaken hard enough.

The USGS has liquefaction hazard maps (which include ground shaking potential) for Northwestern Alameda County, and Northern Santa Clara County (<http://earthquake.usgs.gov/regional/nca/qmap/>)



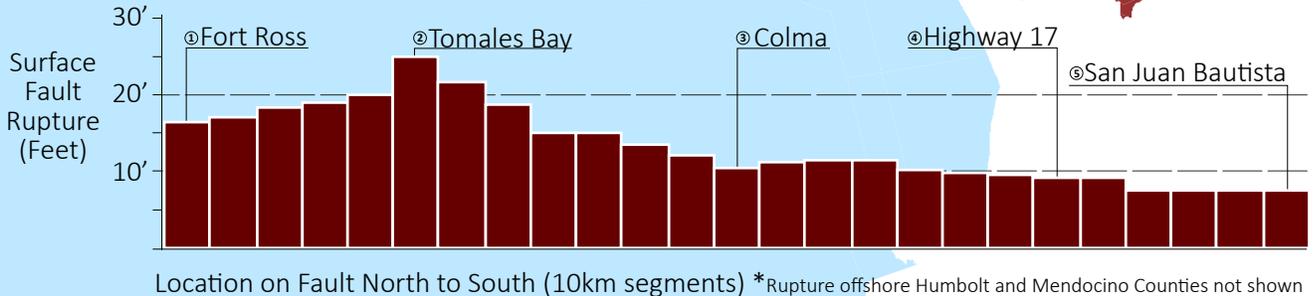
SCENARIO SUMMARY

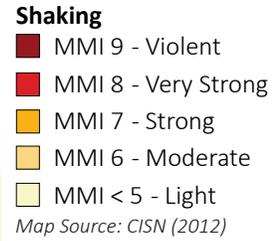
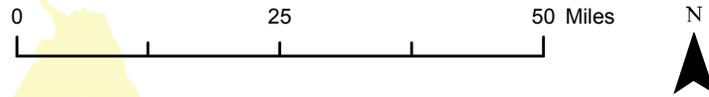
Ground Shaking: Ground shaking in a M7.9 event would cause strong shaking in all nine Bay Area counties, with violent and very strong shaking along the entire Peninsula and Marin County. Smaller fault ruptures on the San Andreas like the M6.9 1989 Loma Prieta earthquake can produce more frequent M6 and low M7 events.

Faulting: The San Andreas fault extends from off the coast of Humboldt County down to Mexico. In 1906 the fault ruptured from Humboldt County to south Santa Clara County. The surface fault rupture in a future M7.9 event could be over 25 feet in some sections (Thatcher, 1997).

Liquefaction: In locations in every county the ground shaking will be strong enough to trigger liquefaction.

M7.9 San Andreas Surface Fault Rupture Displacement (Thatcher, 1997)





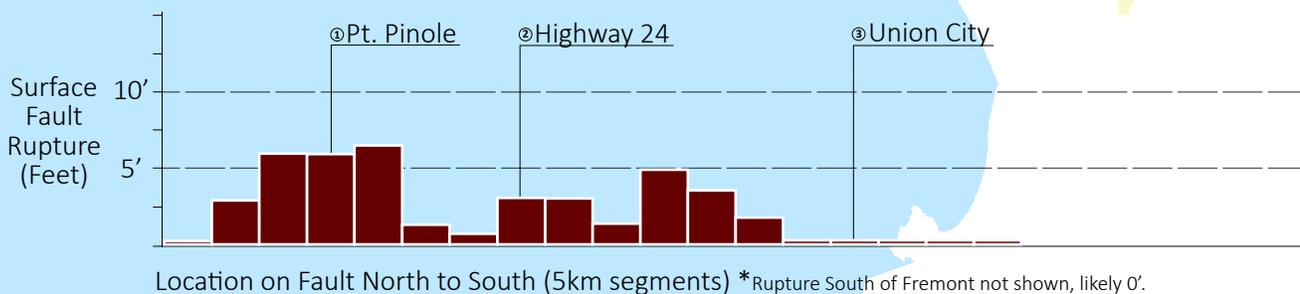
SCENARIO SUMMARY

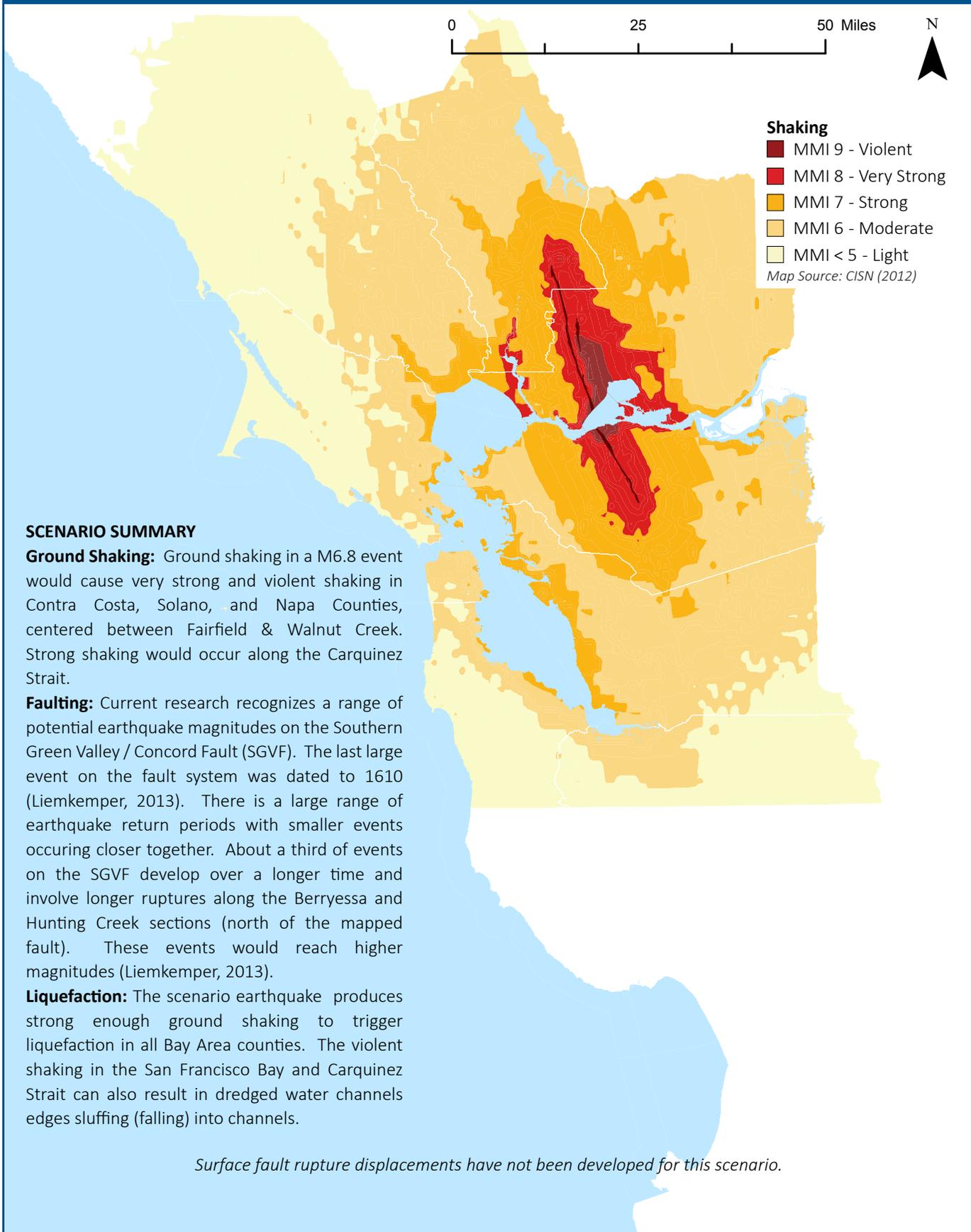
Ground Shaking: Ground shaking in a M7.0 will cause very strong and violent shaking in the East Bay, with the western portion of the region experiencing very strong shaking.

Faulting: The Hayward fault runs from off the shoreline of Pt. Pinole in Richmond to the eastern foothills south of San Jose. This 7.0 scenario is characterized by the entire fault slipping at once. The fault can also produce slightly smaller earthquakes with just the northern or southern portions slipping. Additionally, the Hayward fault is part of the Hayward-Rodgers Creek fault system which continues along the same trajectory North through Sonoma County; Hayward and Rodgers Creek could slip together, generating a larger earthquake.

Liquefaction: In locations in every county the shaking will be strong enough to trigger liquefaction, particularly near the shoreline.

M7.0 Hayward Surface Fault Rupture Displacement (Aagaard, 2012)





SCENARIO SUMMARY

Ground Shaking: Ground shaking in a M6.8 event would cause very strong and violent shaking in Contra Costa, Solano, and Napa Counties, centered between Fairfield & Walnut Creek. Strong shaking would occur along the Carquinez Strait.

Faulting: Current research recognizes a range of potential earthquake magnitudes on the Southern Green Valley / Concord Fault (SGVF). The last large event on the fault system was dated to 1610 (Liemkemper, 2013). There is a large range of earthquake return periods with smaller events occurring closer together. About a third of events on the SGVF develop over a longer time and involve longer ruptures along the Berryessa and Hunting Creek sections (north of the mapped fault). These events would reach higher magnitudes (Liemkemper, 2013).

Liquefaction: The scenario earthquake produces strong enough ground shaking to trigger liquefaction in all Bay Area counties. The violent shaking in the San Francisco Bay and Carquinez Strait can also result in dredged water channels edges sluffing (falling) into channels.

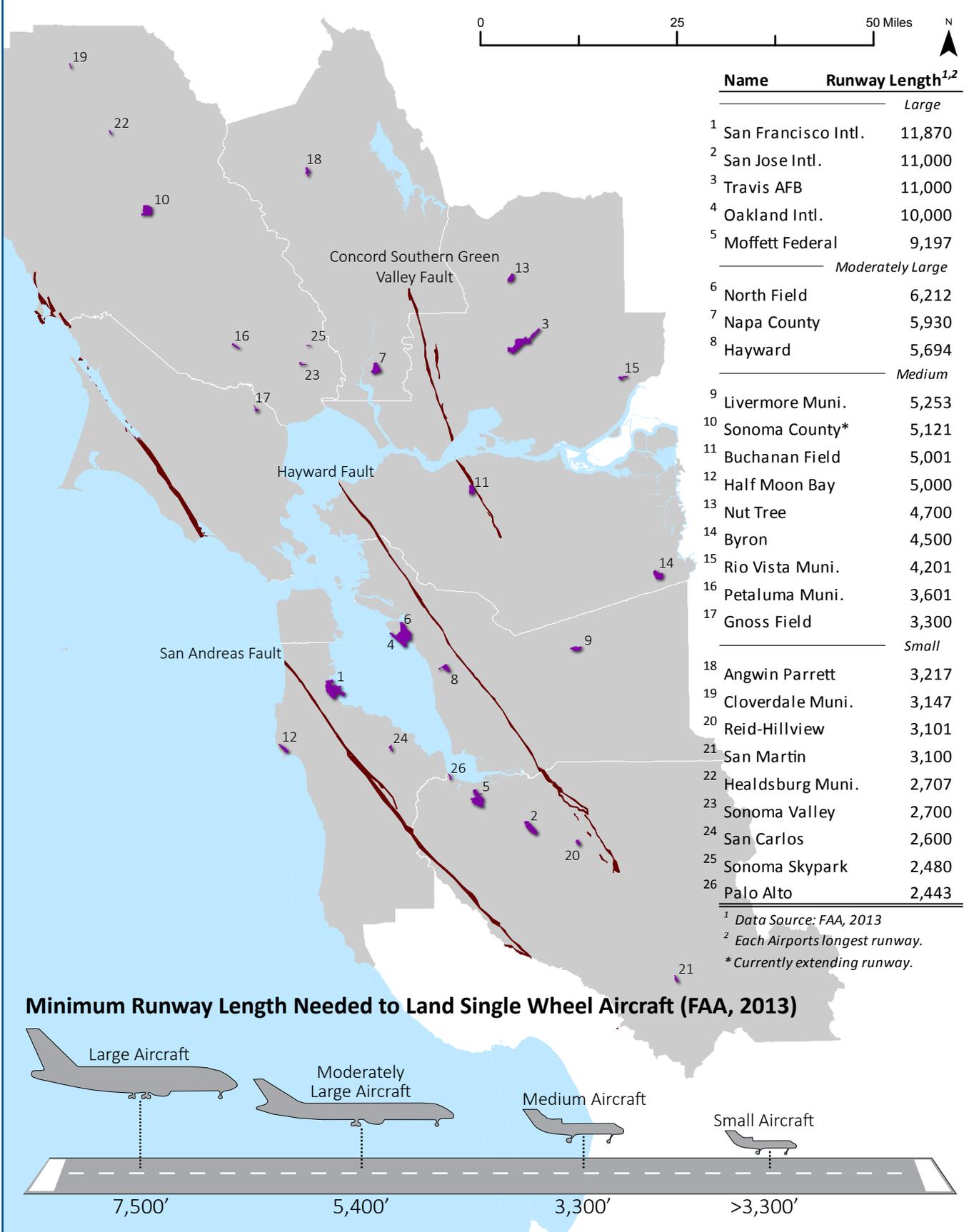
Surface fault rupture displacements have not been developed for this scenario.

AIRPORTS

The Bay Area's 26 airports are well distributed throughout the region; however, in San Andreas and Hayward scenario events, the three international airports will simultaneously experience strong to violent shaking. A 2013 liquefaction report suggests that in both events SFO and OAK will experience a few inches of runway settlement in either San Andreas or Hayward events. SJC is in a susceptible liquefaction zone, but has completed a mitigation project to greatly reduce the risk of significant settlement.

Bay Area airports provide residents and businesses the ability to travel and conduct business across the globe. The airports support the regional economy by providing airport sector jobs, economic access to domestic and global markets, air cargo services, and tourism access. Commercial travel out of the three international airports will be tested by San Andreas and Hayward earthquake events. Four of the region's five airports that can handle large aircraft experience strong to violent shaking in both the San Andreas and Hayward scenarios. In these scenarios Travis Air Force Base in Solano County is the only large runway outside of the strong shaking zone.

Location of Bay Area Airports in Relation to the Three Major Faults



GROUND TRANSPORTATION

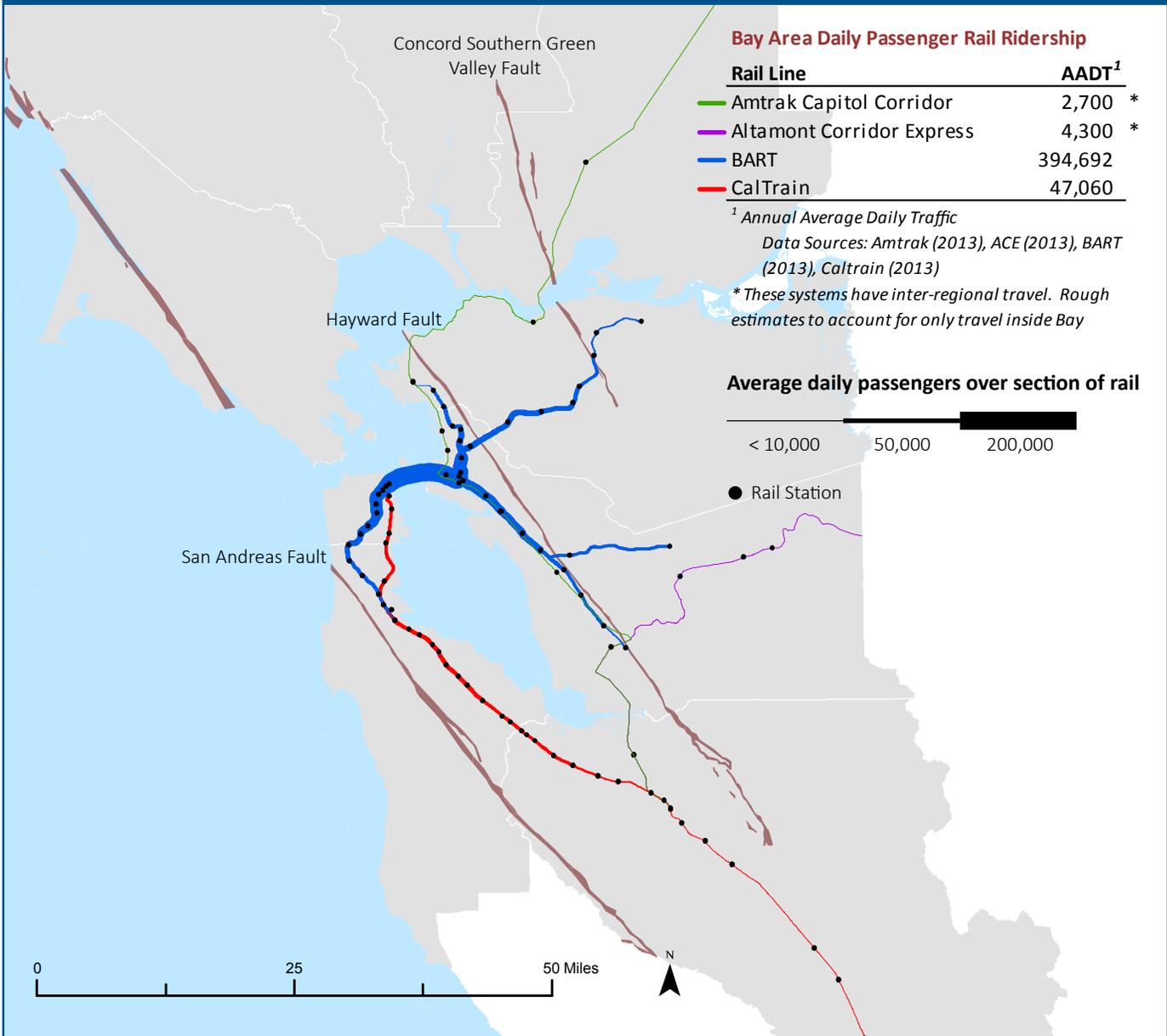
Large-scale seismic retrofit programs have resulted in a much more resilient transportation network. Still a single failure along non-redundant corridors can severely disrupt travel.

The busiest highway corridors in the region are parallel networks (a good thing), but are subject to simultaneous hazards in single scenario events (a bad thing). In a San Andreas event I-280 will experience violent shaking while US 101 will likely experience liquefaction. The same experience occurs in the East Bay in a Hayward event. I-580 zig-zags over the fault three times, while I-880 passes through very-high liquefaction hazard zones. In each case it is possible for the network to be brought to a standstill if the redundant pairs are damaged simultaneously.

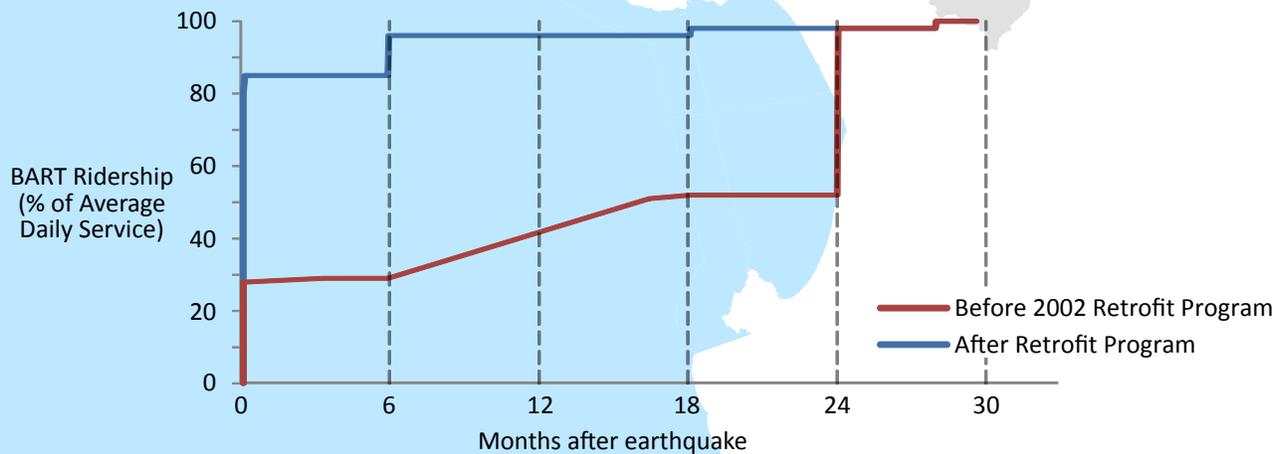
RAIL SYSTEM SUMMARY

An extensive network of both road and rail infrastructure provide the Bay Area region with multiple modes of travel across most of the region. There are four main intra-regional and inter-regional passenger rail services. The figure shows the map of these systems and their respective ridership levels along each section of track. BART expects the majority of their system to be operational very soon after a large earthquake. The figure shows their expected system restoration after a M7.0 Hayward event both before and after their mostly completed seismic retrofit program, which began in 2002 (BART 2002a). The other rail systems are primarily at-grade lines that should be quickly repairable. Altamont, Amtrak, and Caltrain all have at-grade platforms, and for the most part have fewer bridges than most of the highways. In a Concord event, the rail bridge that crosses parallel to the Benicia – Martinez Bridge is only two miles from the Concord fault. In a Concord event, the shaking and/or liquefaction could cause significant or complete damage to the rail bridge.

Passenger Rail Layout & BART Service Restoration following a M7.0 Hayward Event



Expected BART Service Restoration - M7.0 Hayward Earthquake (BART, 2002a)

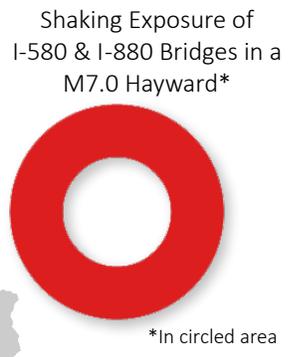
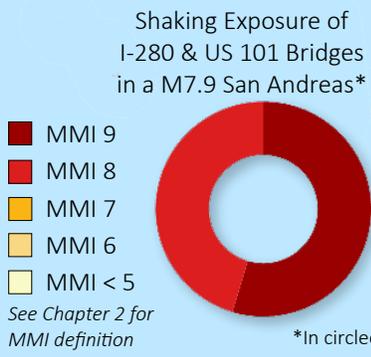
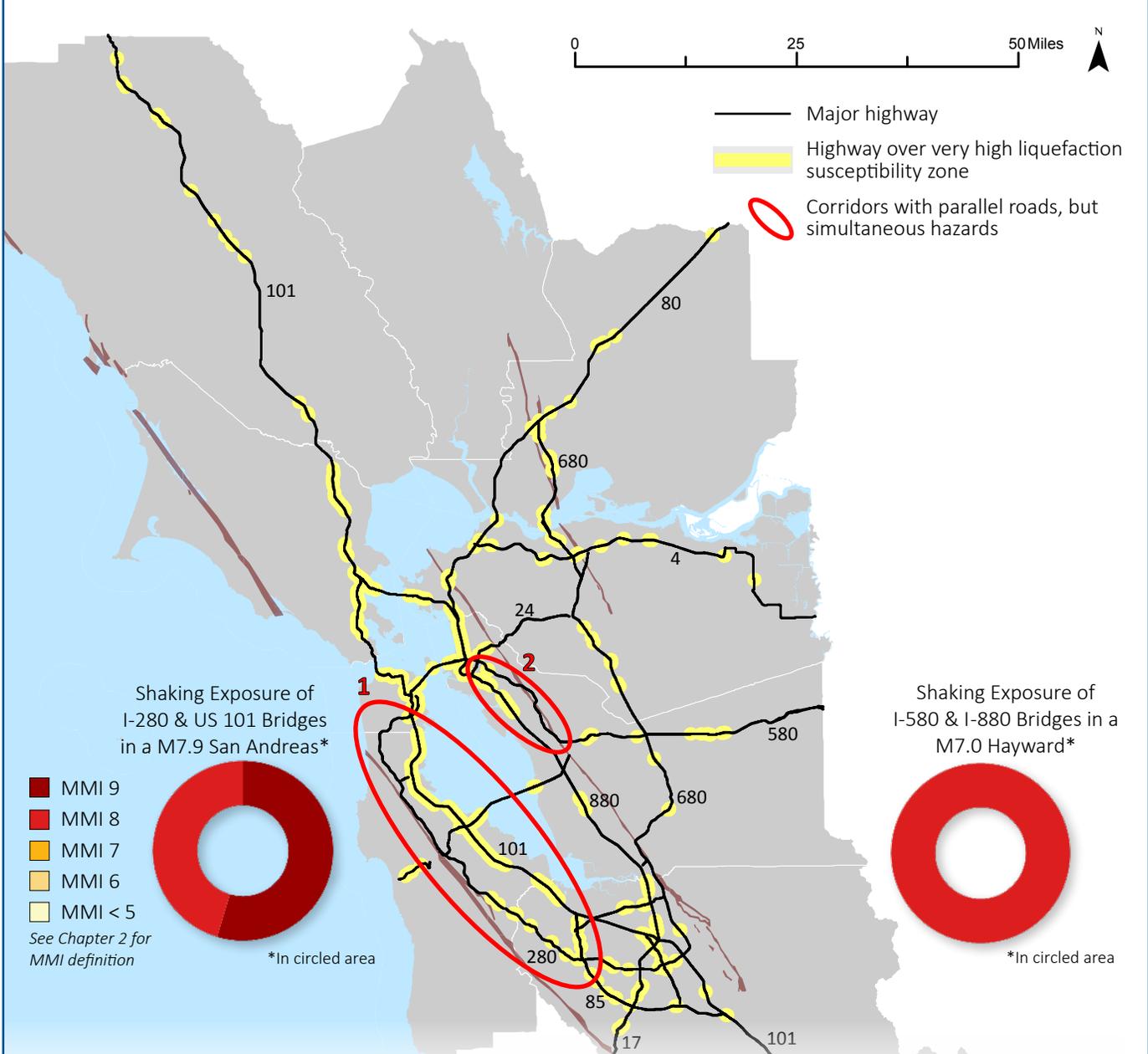


ROADWAY SYSTEM SUMMARY

In the nine county Bay Area region there are over 1,400 miles of state highways, and another 20,000 miles of local roadways (Caltrans, 2011). California road networks have had catastrophic failures in both the 1989 Loma Prieta and 1994 Northridge earthquakes. Since 1989, Caltrans has spent over \$12 billion to seismically strengthen over 2,200 of 12,000 bridges state-wide. Over the past twenty five years since Loma Prieta, the region has seismically retrofitted all bridges that cross the Bay. In 2013, Bay Area Toll Authority (BATA) and Caltrans completed all planned seismic retrofits of bay crossings, including the replacement of the eastern span of the Bay Bridge. The Golden Gate Bridge, which is operated separately, has continually completed seismic retrofits since 1997 and has work scheduled until at least 2018.

“Each [bay crossing] retrofit is designed to a level that, at a minimum, will ensure that the bridge will remain standing in an earthquake. The California Legislature has designated the San Francisco-Oakland Bay Bridge and Benicia-Martinez Bridge as “lifeline structures” since they are located along transportation corridors determined to be crucial to both emergency relief and economic revitalization of the region following a major earthquake. Based on this distinction, the retrofit strategies for these two bridges incorporate some design elements that exceed standard seismic bridge design,” (BATA, 2013).

Liquefaction Susceptibility Along Major Bay Area Highways & Two Corridor Studies



1. The US 101 and I-280 corridor between their San Francisco interchange and the Hwy 85 interchange is exposed to multiple hazards in a M7.9 San Andreas scenario. Over this stretch of I-280 there are 86 bridges, over half of which experience MMI 9 severe shaking. Along this same stretch, over half of the length of US 101 is in a very high liquefaction zone. All bridges along this portion of US 101 experience MMI 8 or 9 as well. Each of these highways have portions that carry over 250,000 daily passengers, with most of US 101 carrying 200,000 daily passengers, and I-280 carrying between 100,000 and 150,000 passengers over this section. In a future San Andreas earthquake, this parallel section of roadway will experience multiple hazards across parallel links.

2. The I-880 and I-580 corridor between the 980 and 238 interchange is exposed to multiple hazards in a M7.0 Hayward scenario. Over this stretch of I-580 there are 44 bridges, all of which will experience MMI 8, very strong shaking. In addition to strong ground shaking, along this stretch of I-580, the road crosses the Hayward fault three times. Along this same stretch, I-880 crosses over many sections of very high liquefaction susceptibility, with all bridges along this portion of the freeway also experiencing MMI 8, very strong shaking. Each of these highways average between 175,000 and 200,000 average daily passengers. In a future Hayward earthquake the parallel section of roadway will experience multiple hazards across parallel links.

FUEL

The Bay Area and all of Northern California are reliant on the five refineries and the Concord pumping station. Because these refineries are located near one another, built on similar soils, and constructed with similar standards, their performance is likely highly correlated. If there is damage to one refinery in an earthquake, it is likely other refineries are also damaged, interrupting a large percentage of the fuel refinement capacity in the Bay Area. If refineries are damaged a conservative restoration estimate is months.

Each studied scenario event will cause significant shaking across a majority of the refineries. These facilities are assumed to be extremely sensitive, as seen in the 2013 Richmond refinery fire when a single pipe failure led to a much more damaging fire. The damage from the fire required eight months to repair. In past earthquakes in Turkey (1999) and Chile (2010), refineries in the shaking region were completely shut down for three months, with limited capacity for over a year.

In addition to the risk of refinery damage, the export of product could be interrupted. All of the refineries export their refined fuel through Kinder Morgan's Concord station. This facility is responsible for pumping fuel across the northern half of the state. The Richmond Chevron refinery also has separate refined fuel pipelines that service Brisbane, and San Jose; however, these pipelines represent a small share of the regional fuel. In Hayward and Concord scenarios, the Concord Station experiences strong and very strong shaking respectively. Additionally, in the Concord scenario there is potential for surface fault rupture that could damage both the station and incoming and outgoing pipelines. Severe damage to the Concord Station or multiple refineries would impact all of Northern California and Northern Nevada. Transporting a normal fuel demand by truck after a disaster simply is not feasible beyond service to the most critical facilities.

California Fuel Production and Use, and the Bay Area's Fuel Profile

CA Gasoline Production	Millions of gallons ¹
Southern Counties	8,545
Northern Counties	6,173
Kern, SLO, SB Counties	1,256
Total³	15,974

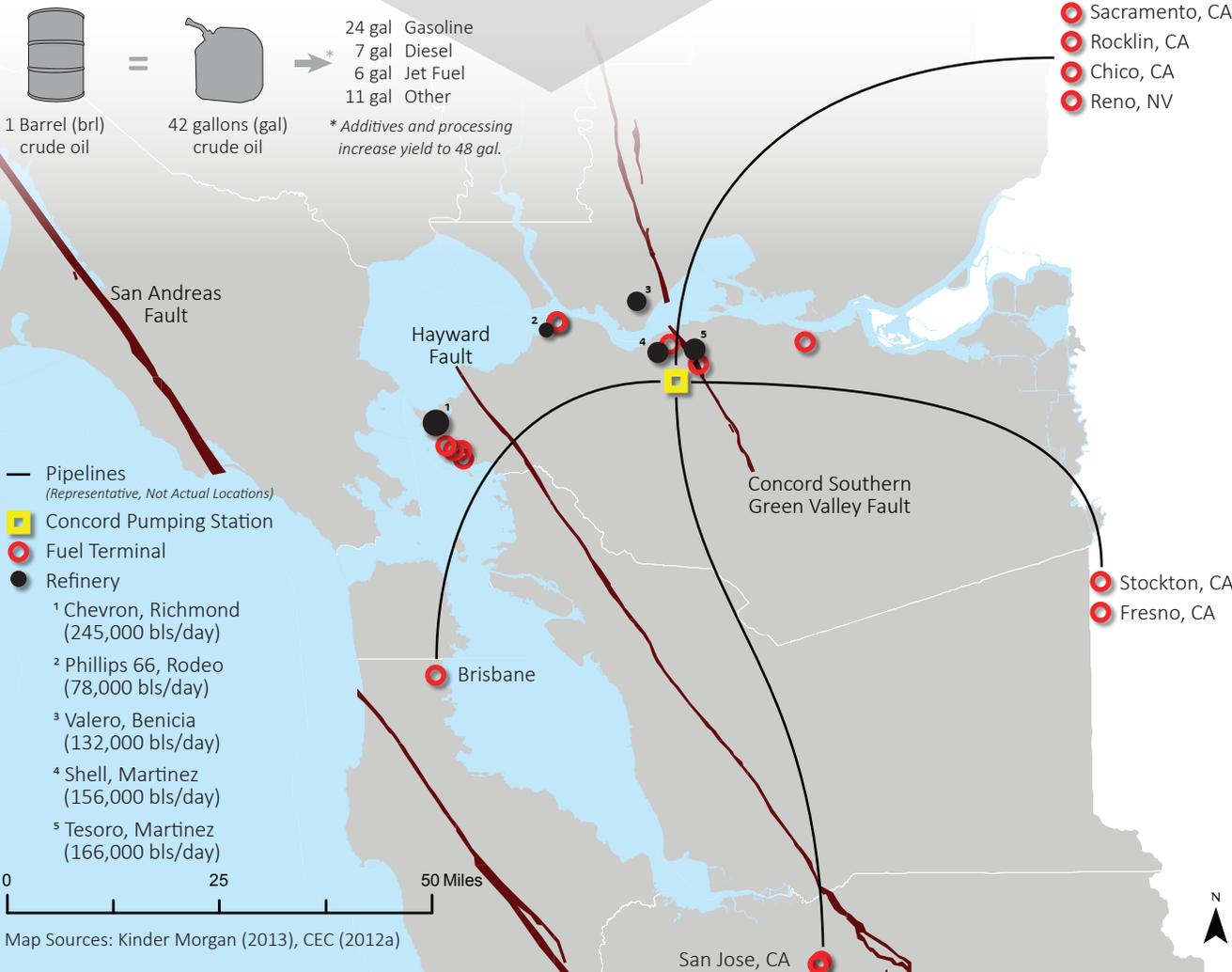
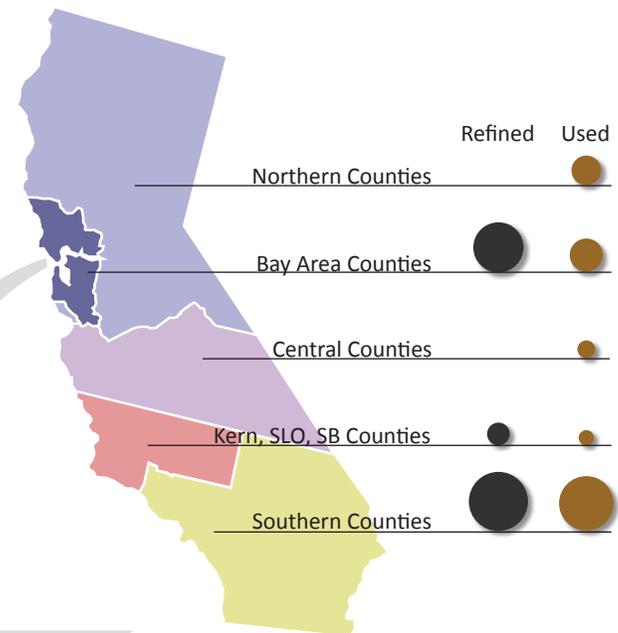
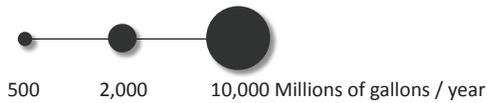
¹ Calculated by multiplying the regional share² by the State total³

² CEC (2012a)

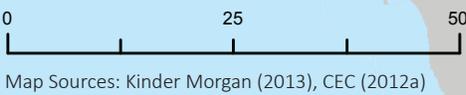
³ CEC (2012b)

CA Gasoline Use	Millions of gallons ¹
Southern Counties	7,247
Bay Area Counties	2,641
Northern Counties	2,151
Central Counties	772
Kern, SLO, SB Counties	572
Total	13,383

¹ CEC (2012c)



- Pipelines
(Representative, Not Actual Locations)
- Concord Pumping Station
- Fuel Terminal
- Refinery
- 1 Chevron, Richmond (245,000 bbls/day)
- 2 Phillips 66, Rodeo (78,000 bbls/day)
- 3 Valero, Benicia (132,000 bbls/day)
- 4 Shell, Martinez (156,000 bbls/day)
- 5 Tesoro, Martinez (166,000 bbls/day)



Map Sources: Kinder Morgan (2013), CEC (2012a)

ELECTRIC

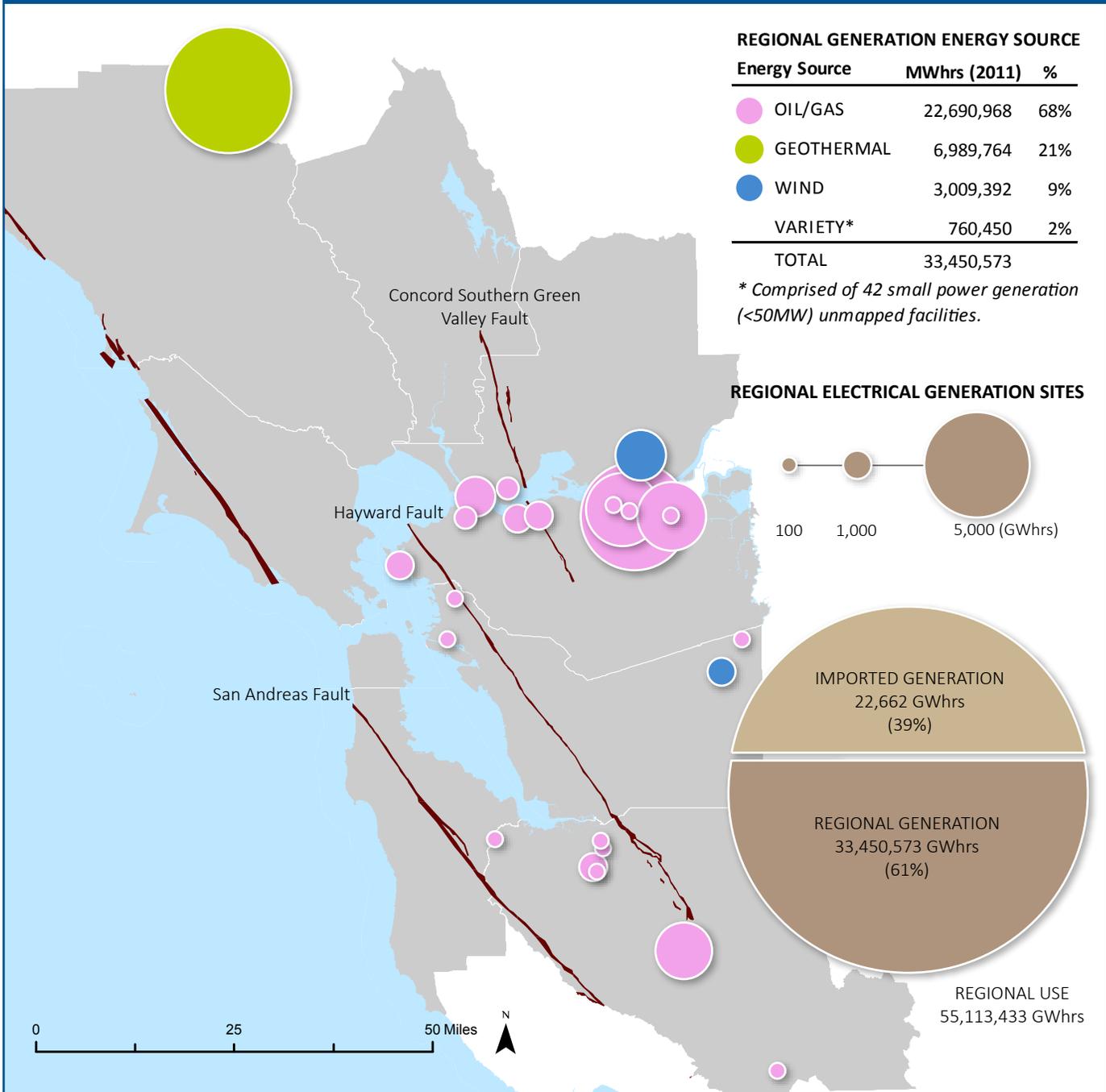
Damage to the region's power generation facilities along the Carquinez Strait, or interruption in the natural gas system could result in long power supply interruptions.

No publicly available data source gives insight into the expected performance of substations, but historic earthquake have shown that substations represent the most fragile portion of the electricity distribution system. There are over 425 substations in the Bay Area with varying degrees of age and investment. There is no publically available source on the varying age or retrofit status of these substations. No analysis could be completed on Bay Area substations.

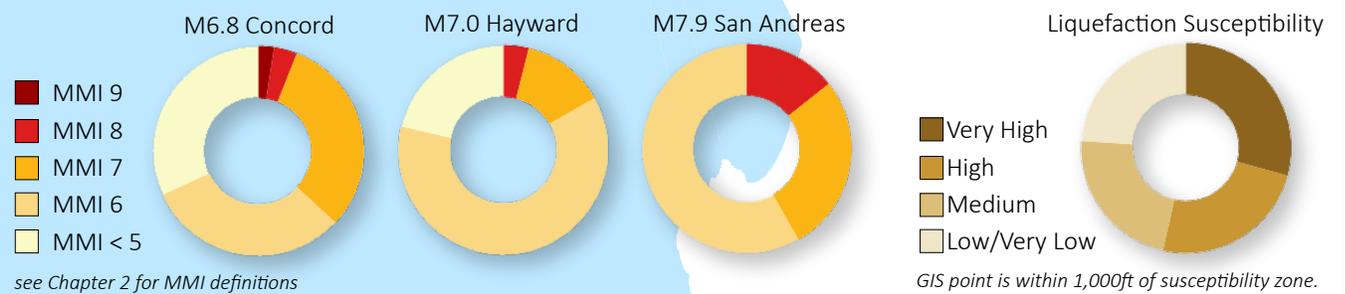
In 2011, the Bay Area consumed 55,000 GWhrs of electricity, 60% of which was generated inside the nine county region (CEC, 2013a; CEC, 2013b). The remaining demand was met by power imports generated elsewhere in the state, the Pacific Northwest, and Southwest. Ninety-eight percent of the regionally produced power is generated at 25 large facilities with the remaining 2% generated at 44 small facilities with less than 50MW capacity. The 25 larger facilities are mapped in the figure.

Based on past earthquake damage and technical report documentation, only the energy generation and substations are likely to cause disruptions for a significant length of time. Of the regionally-generated power, two-thirds is produced by natural gas facilities, which are mostly located along the Carquinez Strait, an area that is bisected by the Concord fault. An interruption of natural gas would impact a large portion of electrical generation.

Electric Generation for the Nine County Bay Area Region and Its Exposure to Seismic Hazard



Regionally Generated Power Exposed in Scenario Earthquake Shaking & Liquefaction Zones (MWhrs)



WATER

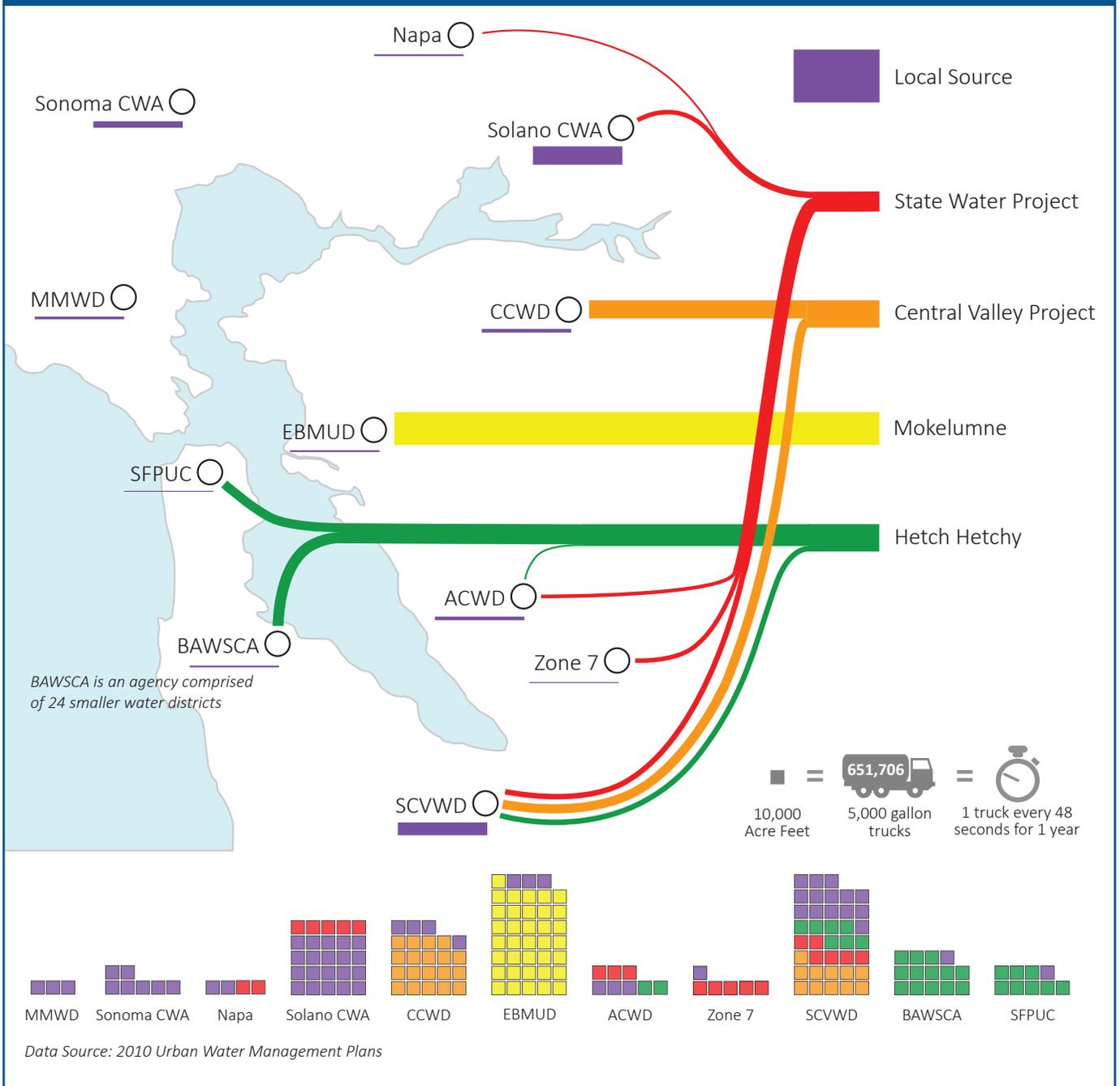
WATER SUPPLY SUMMARY

The Bay Area's water supply comes from a portfolio of sources. The Mokelumne and Hetch Hetchy systems supply the Bay Area exclusively, while both the Central Valley Project and State Water Project supply water to regions across California. The Bay Area's water supply is distributed by 89 different water providers (districts, agencies, and cities). Eleven providers distribute water to 93.7% of the Bay Area's population. This research focuses specifically on the reliability of the region's water transmission systems and the capability of the local water storage to meet water needs if outside sources are interrupted.

Most of the 11 Bay Area water districts studied have multiple water sources or have invested in robust, redundant, and repairable systems that contribute to system resilience. When reservoirs and groundwater reserves are above half full there is significant regional water storage available locally if regional systems require repair. Agencies dependent on Delta water would be significantly impacted if levees failed, causing flooding and salt water intrusion into State Water Project (SWP) and Central Valley Water Project (CVWP) sources.

SFPUC and EBMUD assessed the seismic performance of their own transmission supply systems and have since mitigated their transmission system to be more reliable. Both recognize that their distribution systems remain vulnerable. There is no record of the Central Valley Project (CVP) and State Water Project (SWP) taking comparable action to ensure their systems are functional in an appropriate time scale following a Bay Area Earthquake. Additionally the CVP and SWP systems capture water from the Sacramento-San Joaquin Delta, which is subject to salt water intrusion if levees that hold back water fail, resulting in a long term shut down of the CVP and SWP systems that supply the Southern half of the state (DWR, 2008). *"A moderate to large earthquake in the San Francisco Bay region could cause major damage to Delta and Suisun Marsh levees, and could cause many of them to fail...Seismically induced levee failures would be expected to extend for thousands of feet if not miles and impact many locations simultaneously... For example, there is about a 40 percent chance that 20 or more islands will flood simultaneously as a result of an earthquake sometime over 25 years of exposure."* (DWR, 2008)

Water System Source Portfolio (Eleven Largest Bay Area Water Districts) & Annual Normal Supply



WATER STORAGE SUMMARY

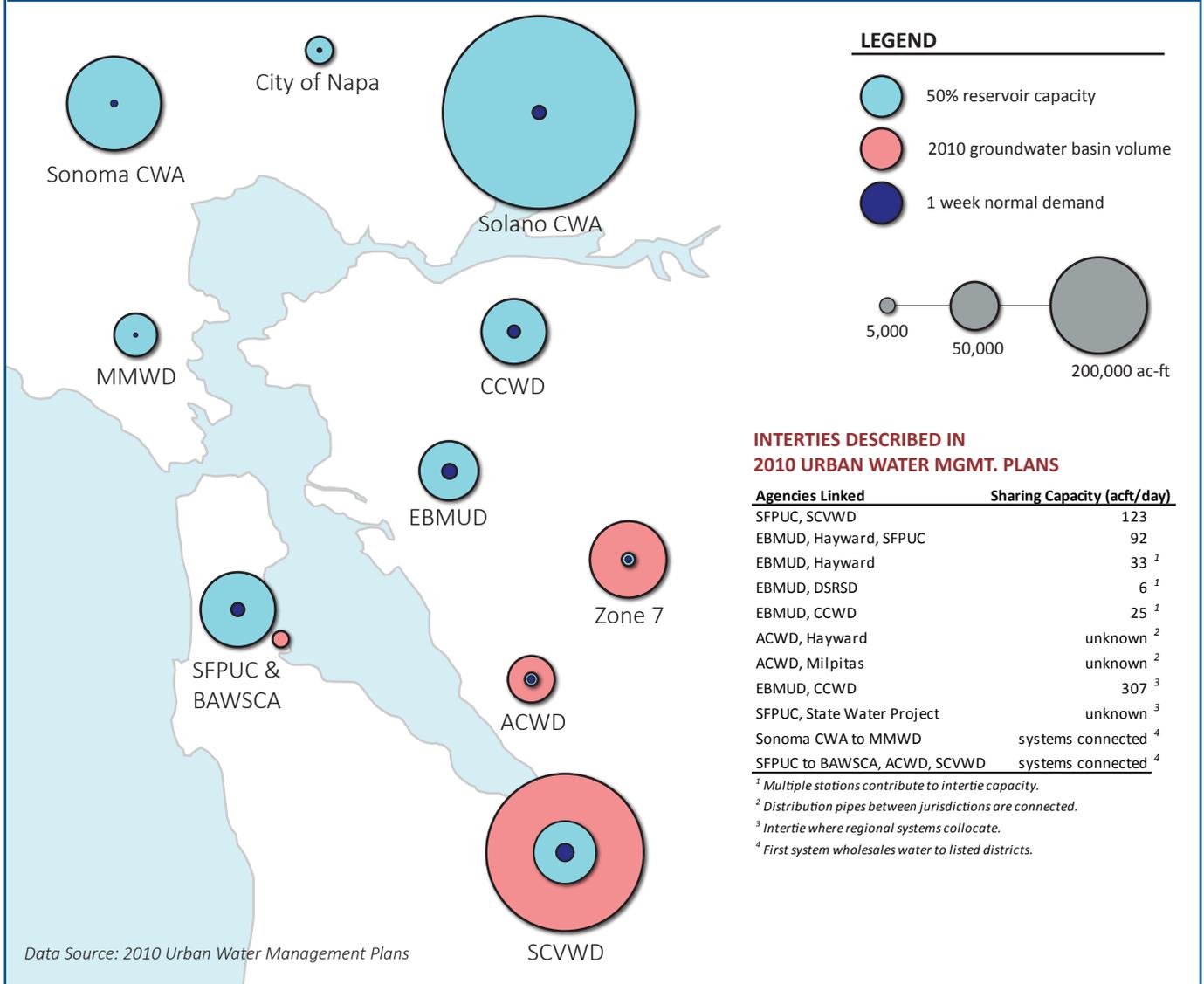
If interruption to out-of-region water sources were to occur, local sources and storage would be relied on until repairs were made to restore the transmission supply for districts reliant on imported water supplies. In communities and economic centers located on the bay margins water distribution pipelines may require weeks or months to repair liquefaction damaged pipes.

Over 200 reservoirs store water in the Bay Area all, with varying owners and operation goals. The 11 main water districts rely on 39 large local reservoirs with a maximum storage capacity of 3 million acre-feet. In addition to surface storage SCVWD, ACWD, and Zone 7 rely on local ground water for a large percentage of their storage and emergency supply. The graphic shows the relationship between a district's average weekly water use and how much water is available when reservoirs are at 50% their total storage capacity. It also includes the addition of local groundwater reserves for the four districts with large aquifers. Within the region, there is capacity for the water system to operate in isolation from the water sources outside the region if local reservoirs are (1) more than half full, (2) ground water reserves are near current levels, and (3) inter-regional systems can be repaired in a few months. In a drought, it is possible that local reserves will not be sufficient to supply water while regional systems are repaired.

To increase redundancy, many agencies have constructed interties, or links, between systems. The interties can be used to share water during the interruption. The capacity of these interties supplies a fraction of the normal demand, but could be used effectively to provide emergency water to some locations.

This study only examines the vulnerability of the regional portions of water systems. An earthquake can cause severe damage to aged distribution pipes, requiring weeks if not months to restore water to all customers.

Water Storage Within Nine County Region, and Normal Water Demand



INTERDEPENDENCIES

Damage caused by the earthquake will be only one source of failures. The failure of one infrastructure system will lead to the failure of other systems and slow the restoration of services.

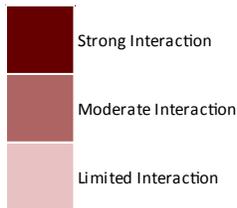
In 2014, the City and County of San Francisco's Lifeline Council, a pioneering council made up of utility operators that service the City, published its first Lifelines Interdependence Study [<http://www.sfgsa.org/index.aspx?page=4964>]. For the study, past research and utility interviews were used to roughly qualify the interdependence between systems. Figure 13 shows the matrix of interdependence between twelve important systems for the City and County of San Francisco. This information was then taken and displayed with lines in a scallop diagram. It is clear from both graphics that fuel is the system most relied on by all other systems. Roads, electricity, telecom, and water were also main systems relied on by others.

The San Francisco study was completed for the City and County of San Francisco. The specific relationship between systems may be different for other cities, but the overall interactions are likely to be fairly similar for the Bay Area region as a whole. The study is an example of the work a Lifelines Council can achieve. The Council has already worked to designate priority routes through the city that are critical for multiple systems restoration, and is currently magnifying its study of cell sites, fuel supplies, and utility staging sites. The Council should be used as a model to address issues of infrastructure vulnerability and interdependence for the Bay Area region.

Reading the matrix from left-to-right shows which systems the designated operator relies on. For example, Airports have a strong interaction with regional roads, but a limited interaction with natural gas.

Reading the matrix from top-to-bottom shows which systems rely on the designated operator. For example, all systems have a strong interaction with the fuel system.

The lifeline operators' dependency on other lifeline systems (read across each row)



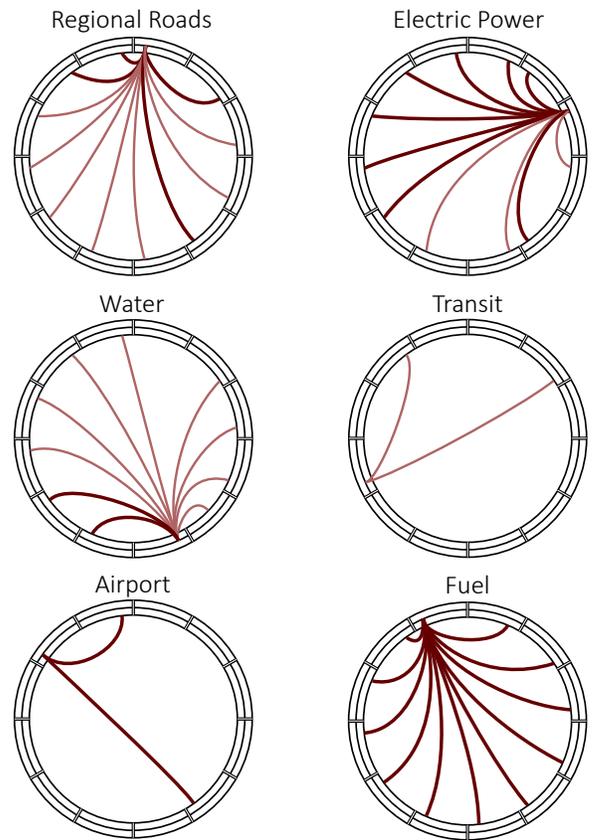
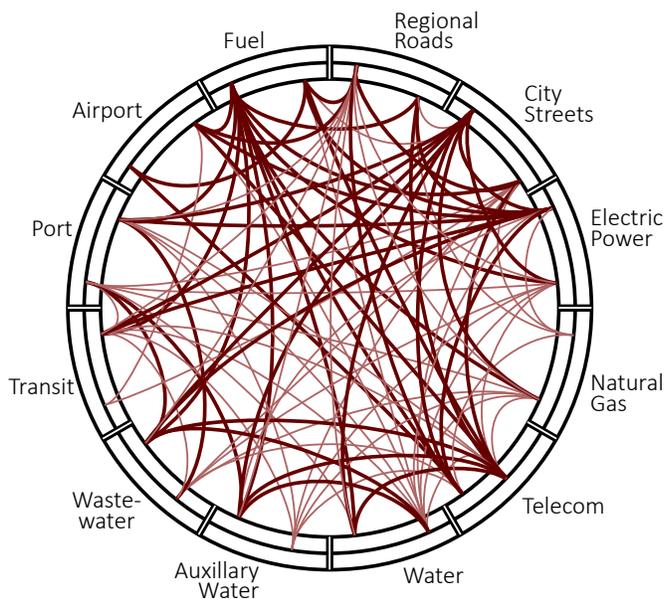
The overall interaction and dependency on a particular system (read down each column)



City & County of San Francisco, 2014

Matrix Information Displayed as Scallop Diagram.

The graphic below shows all moderate and strong interactions between systems. The individual systems to the right show which systems rely on the designated operator (same as reading the matrix from top-to-bottom).



CONCLUSION

Functional infrastructure systems are necessary for achieving community resilience. The consequence of infrastructure damage cascades well beyond the costs to repair the immediate damage. The failure of one system limits the functionality of other key regional assets, and will cause interruption for both households and businesses. While it is unrealistic to expect systems to be earthquake proof, knowing what to expect provides the users of infrastructure systems the information they need to take measured preparedness actions, or advocate for greater reliability. Currently, the vulnerability of many infrastructure systems is not well known or not well communicated to the public. With a lack of information, stakeholders have no baseline for predicting the benefits of possible preparedness or mitigation strategies. Going forward, the region must understand and communicate the vulnerability of infrastructure systems to inform stakeholders on what to expect so that they can make informed decisions to reduce impacts to their home or business should systems fail.

This study is a first step in understanding the risks to transportation, fuel, electric, and water systems. The report should be used to inform actions in the present, and also as a call for greater study and transparency of the region's infrastructure systems.

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